Andrew R. Teel
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Robust Nonlinear Control of Piloted Tailless Fighters

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Affiliation during award period:
Department of Electrical Engineering
University of Minnesota
Minneapolis, MN 55455

Current affiliation:
Department of Elect. & Comp. Eng.
University of California
Santa Barbara, CA 93106

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Tools leading to effective control strategies for tailless fighter aircraft were developed. Emphasis was placed on the development of control algorithms that yield robust performance in the presence of actuator magnitude and rate limits. Significant new tools for anti-windup synthesis were developed. The anti-windup problem is that of synthesizing modifications to an existing control system where the modifications are dormant when actuator limits are not active and the modifications maintain good performance when actuator limits are active. We applied these ideas to control a turbofan engine model, an F-16 model, and Caltech's ``ducted fan'' experiment.

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Minneapolis, MN 55455

Principal Investigator: Andrew R. Teel
(805) 893-3616
teel@ece.ucsb.edu

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Summary

The objective of the research supported by the Air Force Office for Scientific Research under Grant No. AF/F49620-96-1-0144, which ran from April 15 1996 through September 15 1997, was to develop tools leading to effective control strategies for tailless fighter aircraft. Emphasis was placed on the development of control algorithms that yield robust performance in the presence of actuator magnitude and rate limits. The results of our research are documented in the nine papers that are listed in the next section. In these papers we have developed significant new tools for anti-windup synthesis. The anti-windup problem is that of synthesizing modifications to an existing control system where the modification are dormant when actuator limits are not active and the modifications maintain good performance when actuator limits are active. We applied these ideas to control a turbofan engine model, an F-16 model, and Caltech's "ducted fan" experiment.

1 Research Publications

The research supported by this grant resulted in 3 journal papers and 6 refereed conference papers. These papers are listed below.

Journal Papers

1. N. Kapoor, A.R. Teel and P. Daoutidis, "An anti-windup design for linear systems with input saturation", *Automatica*, no. 5, pp. 559-574, 1998.

2. A.R. Teel, "Connections between Razumikhin-type theorems and the ISS nonlinear small gain theorem", *IEEE Transactions on Automatic Control*, July 1998, vol. 43, no. 7, pp. 960–964.

3. A.R. Teel, "Anti-windup for exponentially unstable linear systems", *International Journal of Robust and Nonlinear Control*, **9**, 701-716 (1999).

Refereed Conference Papers

4. Kapoor, N., A.R. Teel, and P. Daoutidis, "An invariant subspace technique for anti-windup synthesis", In *Proceedings of the 1997 American Control Conference*, Albuquerque, NM, pp. 3083–3087.

5. Teel, A.R. and N. Kapoor, "The $\mathcal{L}_2$ anti-windup problem: its definition and solution", *1997 European Control Conference*, (CD-ROM) Conference ID no. 494.

6. Teel, A.R. and N. Kapoor, "Uniting local and global controllers", *1997 European Control Conference*, (CD-ROM) Conference ID no. 959.

7. Teel, A.R. and O.E. Kaiser and R.M. Murray, "Uniting local and global controllers for the Caltech ducted fan", In *Proceedings of the 1997 American Control Conference*, pp. 1539–1543, Albuquerque, NM, 1997.

8. Teel, A.R. and J.M. Buffington, "Anti-windup for an F-16's daisy chain control allocator". In *Proceedings of the AIAA Guidance, Navigation and Control Conference*, pp. 748–754, New Orleans, LA, 1997.

9. Kapoor, N. and A.R. Teel, "A dynamic windup compensation scheme applied to a turbofan engine", In *Proceedings of the 36th IEEE Conference on Decision and Control*, pp. 4689–4694, San Diego, CA, December 1997.

2 Research Accomplishments

2.1 Uniting local and global controllers

One of our premises for this work was that controllers that give good local performance are being scrapped (or modified in an ad-hoc manner) because they don't cope well with nonlinearities activated during the transient response. This is especially true for controllers that interact adversely with constraints on input magnitude and rate. For linear systems with input saturation, there exist numerous heuristic ideas for modifying a predetermined linear compensator to try to mitigate the influence of input saturation. If simulation results do not indicate success, the original controller is usually discarded and replaced by a new controller with less ambitious performance goals.

Our immediate research goal was to develop a systematic method for modifying local performance controllers only when troublesome nonlinearities become significant. Our paradigm was to move from looking for a *substitute* to looking for a *supplement.* One area of research that informs our modifications is that of nonlinear control which typically focuses more on stability issues in the face of nonlinearities rather than on performance.

We succeeded in developing an algorithm that dynamically supplements a local, performance controller with a reduced performance, 'global' controller when troublesome nonlinearities become significant.

Successful synthesis requires the following:

- a local performance controller (the scrapped one);
- a 'global' controller (e.g., the former substitute or something from nonlinear control theory);
- a fairly accurate model of the process.

Despite the last requirement, robustness can be easily analyzed and our case studies indicate robustness to process uncertainty.

The complete, nonlinear algorithm is described in [1]. There it is pointed out, for example, how the algorithm can be used for fully-actuated Euler-Lagrange systems with input saturation to combine decoupling "computed-torque" plus PI controllers with passivity-based stabilizing controllers to give robust, local decoupling and global stability. The algorithm can also be used to combine controllers that use different classes of sensors. For example, one could combine a local, output feedback compensator with a global state feedback compensator in such a way that the state feedback is only used when the state is large and the (otherwise significant) sensor noise is relatively small compared to the size of the state. Perhaps foremost, if an expert in linear control theory has provided a linear compensator that optimizes some performance criteria locally and an expert in nonlinear control theory has provided a nonlinear controller that ensures some form of global stability, we have shown how these two controllers can be elegantly united to obtain optimized local performance and global stability simultaneously.

2.2 Anti-windup synthesis

In [2], we specialized the above-mentioned algorithm to the case where the only nonlinearity comes from a constraint on the input magnitude. The problem of maintaining local performance with a graceful degradation of performance when saturation is encountered is usually referred to as the "anti-windup" synthesis problem. We formalized this problem in [2], describing it as the problem of making small the $\mathcal{L}_2$ (or $\mathcal{L}_p$) gain from, loosely speaking, $u_{nom}(\cdot) - \text{sat}(u_{nom}(\cdot))$ to $(z - z_{nom})(\cdot)$ where $u_{nom}(\cdot)$ and $z_{nom}(\cdot)$ are, respectively, the input and output signals in the case where there is no input saturation.

We have shown that this input-output map can be made globally stable as long as the plant has no eigenvalues with positive real part. Here we draw on recent results on $\mathcal{L}_2$ stabilization of linear systems with input saturation. The gain can be made finite if the plant is Hurwitz. The *local* gain can be made finite without requiring any condition on the poles of the plant. We then produced results of a "global" nature for plants with exponentially unstable modes in [3]. All of these results, the first of their kind, generalize some initial results of this project which were documented in [4] and [5].

2.3 Numerical investigations

We applied our algorithm to various prototype systems that help to understand how it will perform on tailless fighter aircraft.

In one case [6], with Jim Buffington at Wright Laboratory, we used the algorithm to supplement a daisy-chain control allocation-based compensator for the VISTA/MATV F-16 to eliminate oscillations and instability that arise due to limits on pitch thrust vectoring. Consequently, we showed that daisy-chain control allocation can be used in the presence of rate limits as long as it is properly supplemented. This result was unexpected, given previous results that had appeared in the literature. We also showed, by simulation, robustness to unmodeled actuator dynamics.

In another case [7], we applied the algorithm to the Caltech ducted fan to combine a high-gain linear controller that yields a nice step response in the absence of rate limits but is unstable with input rate limits with a low-gain linear controller that yields a sluggish step response but is still stable with input rate limits. We synthesized our combination of controllers for the ducted fan assuming a linear model for the ducted fan. Then nonlinear simulations based on wind-tunnel data were carried out as well as experiments on the actual hardware. Both indicated success of the algorithm and robustness to process uncertainty.

Another application was to a turbofan engine model, in collaboration with Navneet Kapoor at General Electric Research & Development [8]. Again, the algorithm was able to induce desired local performance and, at the same time, make sure that performance was not severely degraded at the onset of actuator saturation.

2.4 Time delays

Consideration of time delays between sensor measurements and actuator actions is an important part of any control design algorithm. The analysis of nonlinear systems with time delays is a very challenging task. In [9] we provided a novel analysis tool for establishing stability with respect to exogenous disturbances for systems with time delays. This was accomplished by exploiting earlier work of the PI on the nonlinear small gain theorem for interconnected nonlinear systems. This analysis tool can be used to predict the performance of aggressive flight control systems that are subject to time delays.

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[1] Teel, A.R. and N. Kapoor. "Uniting local and global controllers", *1997 European Control Conference*, Conference ID no. 959.

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[3] A.R. Teel, "Anti-windup for exponentially unstable linear systems", *International Journal of Robust and Nonlinear Control*, **9**, 701-716 (1999).

[4] N. Kapoor, A.R. Teel and P. Daoutidis, "An anti-windup design for linear systems with input saturation", *Automatica*, no. 5, pp. 559-574, 1998.

[5] Kapoor, N. and A.R. Teel and P. Daoutidis. "An Invariant Subspace Technique for Anti-windup Synthesis", In *Proceedings of the 1997 American Control Conference*, Albuquerque, NM, pp. 3083–3087.

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[9] A.R. Teel, "Connections between Razumikhin-type theorems and the ISS nonlinear small gain theorem", *IEEE Transactions on Automatic Control*, July 1998, vol. 43, no. 7, p. 960–964.

3 Technology transitions or transfer

None.

4 Personnel

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Students supported:	Hui Jin (Ph.D. candidate)